21TDMC GROUP OY

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TECHNOLOGY COMPARISON

"TECHNOLOGIES TO CONVERT LOW-GRADE WASTE HEAT TO ELECTRICITY MUST PRODUCE HIGH POWER DENSITIES AND BE EFFICIENT, SCALABLE, AND COST-EFFECTIVE, BUT SO FAR NO APPROACH HAS MET ALL THESE GOALS."

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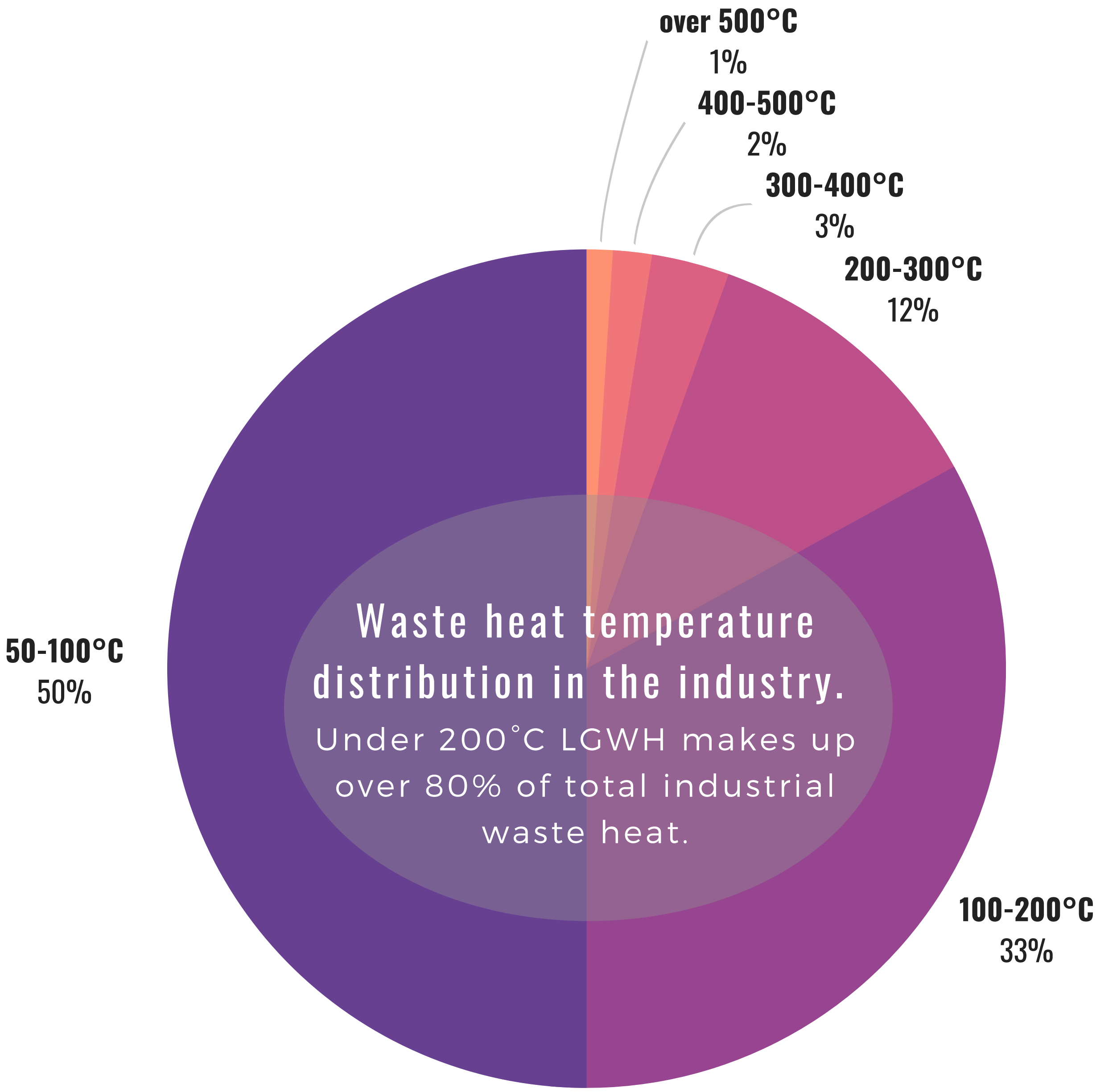
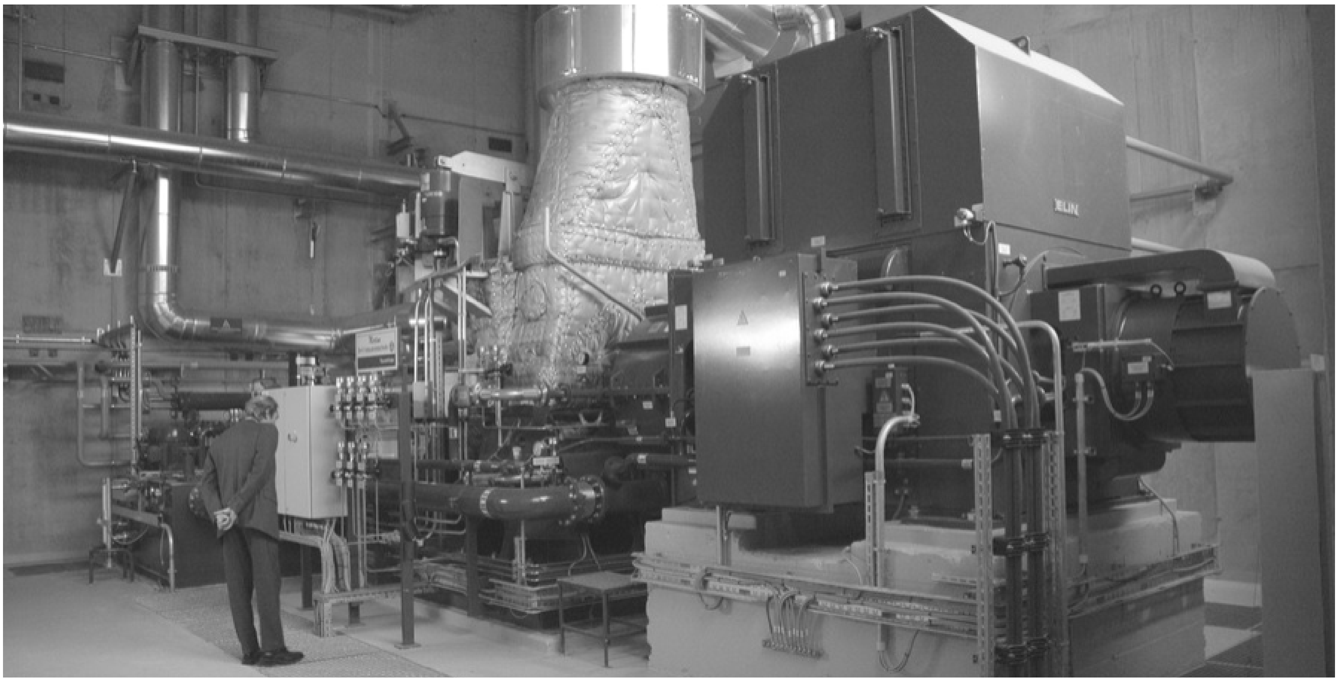
INTRODUCTION

Some studies estimated that about 20-50% of the industrial energy consumption is discharged as heat. Waste heat recovery methods have shown a great development, however there is still a big potential in their improvement. Depending on the application, the heat can be the desired product or can be the input to another process to generate clean electricity. In case a certain quantity and quality of waste heat is available, it is recommended to invest to some kind of heat utilization facility. If we do so, we can spare money and lower the emission from our devices which are beneficial both for us and for our environment. Wast majority of the industrial waste heat consists of Low Grade Waste Heat (LGWH), which offers an enormous growth potential for technologies that can fulfill key parameters required for a commercial implementations, including scalability, efficiency and cost effectiveness.



TECHNOLOGY OVERVIEW



The most used technology for low-grade waste heat recovery is ORC, Organic Rankine Cycle, including different variations and improvements of the technology, although it's not very efficient with the ultra-low-grade waste heat. There are some promising technologies under development, but most of them are either too expensive or otherwise not scalable to a reasonable size for competing with the ORC.

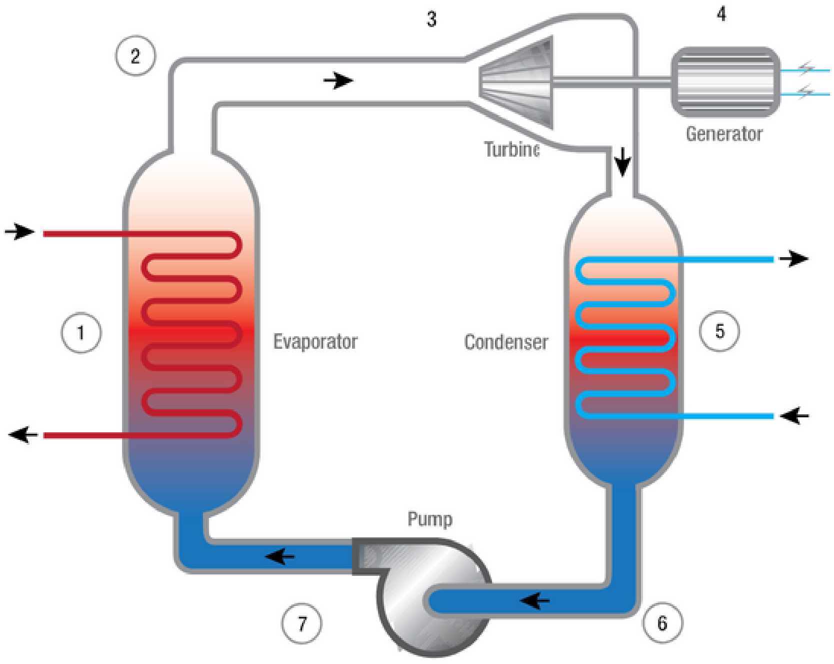
In this presentation, a collection of existing technologies to recover low waste heat is presented. The organic Rankine cycles are the most famous in this field, however their efficiency depend on the selection of the working fluid, which can change from an application to another. The Kalina cycles are more complex and cannot be compared easily to the organic Rankine cycle ORC. The superheated Rankine cycle SRC might have a great future potential, however yet there is a lack in the conducted studies on the CO2 cycles. There are also some new promising technologies presented. The advantages could enable technologies to compete with the conventional Rankine-Hirn cycles. However, additional efforts must be dedicated to design, build and test within an experimental investigation of the performance of most of the new emerging technologies.

1. ORC (ORGANIC RANKINE CYCLE)

The Organic Rankine Cycle (ORC) converts thermal energy into electricity using a process similar to a steam turbine, but it uses refrigerant instead of water. This allows the ORC to extract energy from low-temperature sources.

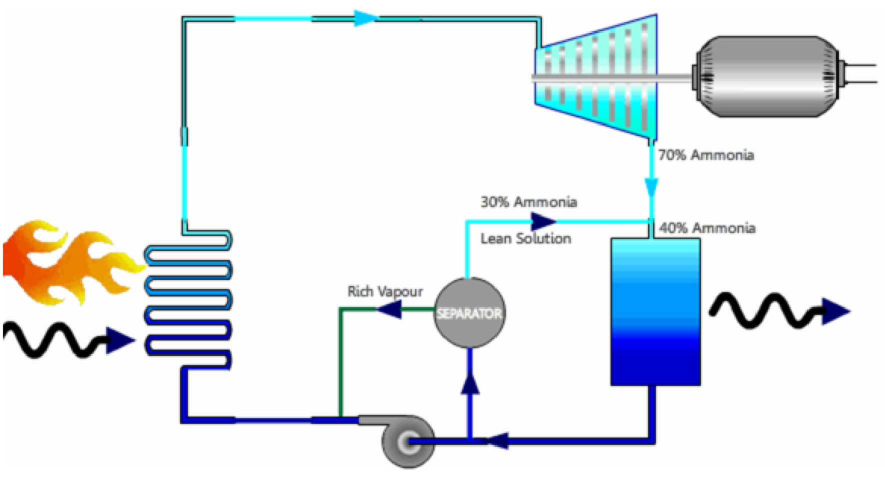
The technology was developed in the late 1950s by Lucien Bronicki and Harry Zvi Tabor. Many improvements for different implementations have been established since, but the central principle has been the same as described below:

1. The heat source transfers thermal energy into the refrigerant causing it to vaporize.
2. High pressure refrigerant vapor flows into the turbine. The refrigerant vapor pushes against the turbine and causes it to spin.
3. The turbine turns the generator producing electrical power.
4. Cooling water extracts thermal energy from the low pressure refrigerant vapor.
5. The refrigerant is condensed back into liquid.
6. Liquid refrigerant is pumped into the evaporator..



KALINA CYCLE

The Kalina cycle is an evolution of the Rankine cycle using an ammonia/water mixture as the working fluid. The mixture does not fully evaporate in the evaporator; a separator is thus required to unload the unevaporated fraction going through the turbine.



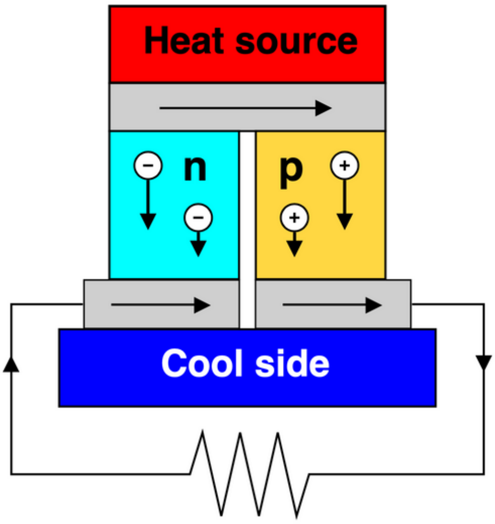
+ Highly scalable up to MWs
+ Highly improved technology
+ Available in market

- Not efficient with the ultra-low grade waste heat
- Expensive technology with a long payback time

2. TEG (THERMOELECTRIC GENERATOR)

A thermoelectric generator (TEG), also called a Seebeck generator, is a solid state device that converts heat flux (temperature differences) directly into electrical energy through a phenomenon called the Seebeck effect (a form of thermoelectric effect). Thermoelectric generators function like heat engines, but are less bulky and have no moving parts. However, TEGs are typically more expensive and less efficient.

A thermoelectric module is a circuit containing thermoelectric materials which generates electricity from heat directly. A thermoelectric module consists of two dissimilar thermoelectric materials joined at their ends: an n-type (negatively charged), and a p-type (positively charged) semiconductor. A direct electric current will flow in the circuit when there is a temperature difference between the ends of the materials. Generally, the current magnitude is directly proportional to the temperature difference..



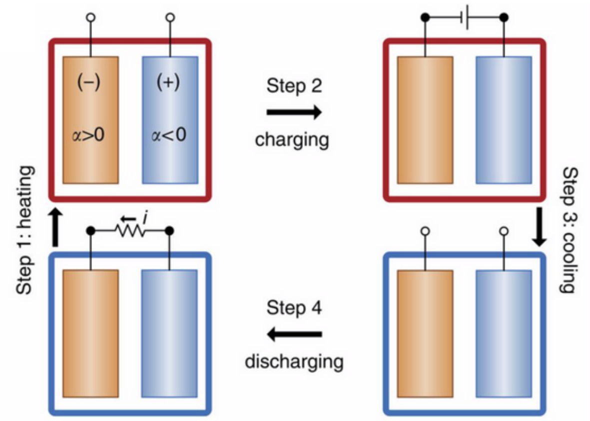
+ Improved technology
+ Available in market
+ suitable with LGWH

- Not scalable to significant production
- Very low efficiency
- Expensive technology for energy production

3. TREC (THERMALLY REGENERATIVE ELECTROCHEMICAL CYCLE)

An alternative approach of the electrochemical system for thermal energy harvesting is to explore thermodynamic cycle as in thermomechanical engines, an efficient thermally regenerative electrochemical cycle (TREC) based on the thermogalvanic effect, the temperature dependence of electrode potential. The concept of TREC has developed a few decades ago for high-temperature applications (500–1,500 °C) and showed an efficiency of 40–50% of the Carnot limit. New experiments and studies with new materials have proven the technology capable of producing energy from the ultra-low-grade waste heat with relatively high efficiency (5,7%). Another similar technology is called thermal capacitive electrochemical cycle (TCEC), which shows a bit lower ability (3% efficiency).

The uncharged battery is heated by the waste heat. Then, while at the higher temperature, the battery is charged; once fully charged, it is allowed to cool. Because the charging voltage is lower at high temperatures than at low temperatures, once it has cooled the battery can actually deliver more electricity than what was used to charge it.



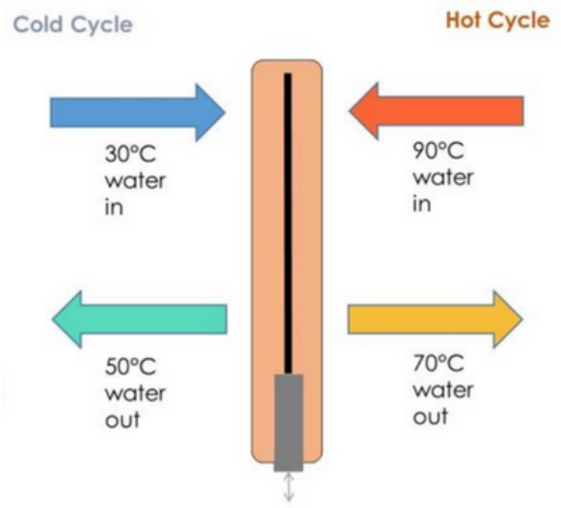
+ More efficient than TEG
+ Suitable with LGWH

- New technology
- Not available in market
- Price/Kw or scalability unknown

4. SME (SHAPE MEMORY EFFECT) HEAT ENGINES

The fundamental phenomenon utilized in the technology which underpins the energy conversion is the contraction of a shape memory alloy (SMA) wire when heated. This occurs as a result of the Shape Memory Effect. Nitinol is an example of an SMA comprising of nickel and titanium. Nitinol undergoes a solid-state phase change when heated, changing from martensite to austenite, where the austenite state is 2-4% shorter in length. In doing so, a single wire can lift tens of kilograms. When cooled, the material returns to its martensite state and size. Thermally cycling an SMA wire will cause a high force linear movement.

The work of the phase change from martensite to austenite can be converted to hydraulic pressure, running a high torque rotary motion via a transmission system and this rotary motion is used to produce electricity by operating a generator. The generator is driven by the hydraulic pressure produced by the SMA deformation. A standard hydraulic generator is used to convert the hydraulic energy into power.



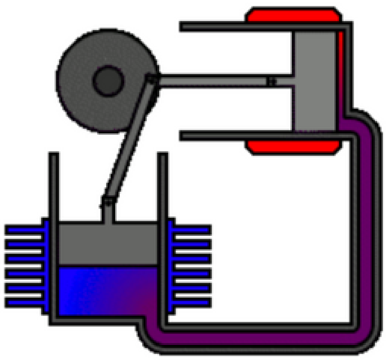
+ Available in the market
+ Low maintenance costs
+ Suitable with LGWH

- Very low efficiency (1,4%)
- Limited scalability (available up to 15 kW)

5. STIRLING ENGINES

The Stirling engine is a closed-cycle regenerative heat engine with a permanently gaseous working fluid, invented and patented in 1816 by mr. Robert Stirling. In contrast to internal combustion engines, Stirling engines have the potential to use renewable heat sources more easily, and to be quieter and more reliable with lower maintenance. They are preferred for applications that value these unique advantages, particularly if the cost per unit energy generated is more important than the capital cost per unit power. On this basis, Stirling engines are cost competitive up to about 100 kW.

Alpha-type Stirling engine. There are two cylinders. The expansion cylinder (red) is maintained at a high temperature while the compression cylinder (blue) is cooled. The passage between the two cylinders contains the regenerator.

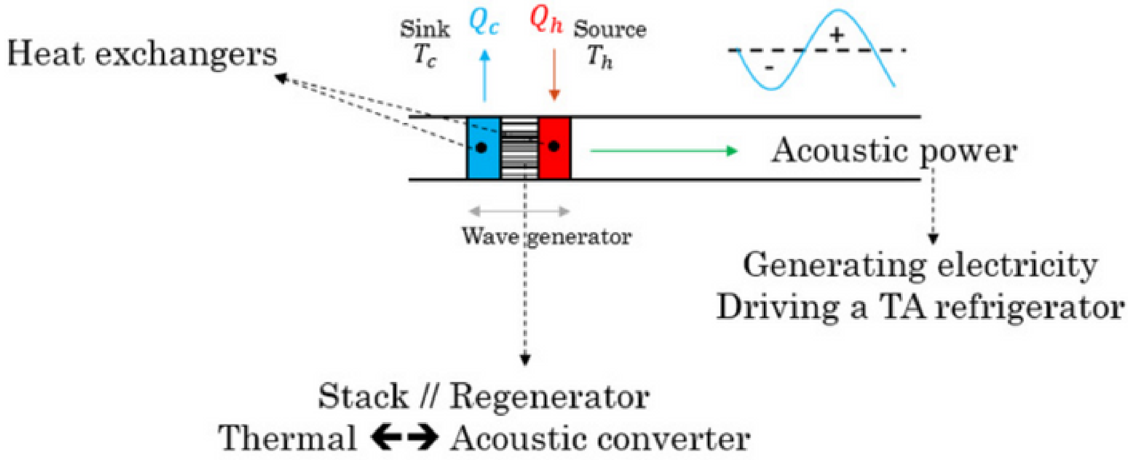


+ Available in the market
+ Improved technology

- Not economically scalable to MWs
- Problems with lubrication and clogging
- Not efficient with the ultra-low grade waste heat

6. THE (THERMOACOUSTIC HEAT ENGINE)

THE is a promising new technology that is able to capture waste heat and produce acoustic energy. The acoustic energy is then used to drive a thermoacoustic cooler or simply moves a solid piston sealed to a moving rod in a magnetic field in a linear alternator to generate electricity. In general, THE as an engine resembles the Stirling engine.



+ simple and reliable
+ Relatively high efficiency
+ Low cost

- Requires relatively high and stabile heat
- Difficult to scale

21TDMC TECHNOLOGY

COMPARISON CHART

	AVAILABLE TECHNOLOGY	SCALABLE TECHNOLOGY	COST EFFECTIVE	CHEAP UNIT PRICE	HIGH EFFICIENCY WITH LGWH	MECHANICAL (SHAFT) POWER	DIRECT ELECTRICITY
ORC	✓	✓				✓	
TEG	✓			✓			✓
TREC				✓			✓
SME ENGINES	✓					✓	
STIRLING ENGINES	✓					✓	
THE ENGINES						✓	
21TDMC TECHNOLOGY*		✓	✓		✓	✓	

*21TDMC technology description only disclosed with a signed NDA.

LINKS

https://www.interreg-central.eu/Content.Node/CE-HEAT/Low-grade-waste-heat-utilization-in-the-European-Union.html

ORC
https://www.sciencedirect.com/science/article/pii/S1364032113000592
https://www.epa.gov/sites/production/files/2015-07/documents/waste_heat_to_power_systems.pdf

TEG
http://engin1000.pbworks.com/f/TE_rev.pdf
https://www.researchgate.net/publication/45523927_Development_of_low_grade_waste_heat_thermoelectric_power_generator

TREC
https://www.frontiersin.org/articles/10.3389/fmech.2017.00020/full
https://www.sciencedirect.com/science/article/pii/S0306261915015020
https://www.nature.com/articles/ncomms4942
https://www.nrel.gov/docs/legosti/old/416_v1.pdf

SME engines
https://ac.els-cdn.com/S1876610217328357/1-s2.0-S1876610217328357-main.pdf?_tid=ec4f15ed-32eb-489d-a84d-8c97c6e92f73&acdnat=1541406872_51f3ec57ced93897156d627c128c85f7
https://www.sciencedirect.com/science/article/pii/S1876610217328357

Stirling engines
https://www.researchgate.net/publication/268220351_Harvesting_Electrical_Power_from_Waste_Heat_Using_Stirling_Engine
http://www.nmri.go.jp/oldpages/eng/khirata/list/ecoboy/lowtemp.pdf

THE engines
https://www.sciencedirect.com/science/article/pii/S1876610214008613
https://www.researchgate.net/publication/12444316_A_thermoacoustic-Stirling_heat_engine_Detailed_study